Perceptual Color Spaces

Background

- Humans can perceive thousands of colors, and only about a couple of dozen gray shades (cones/rods)
- Divided into two major areas: full color and pseudo color processing
  - Full color – image is acquired with a full-color sensor like TV camera or color scanner
  - Pseudo color – Assign a color to a range of monochrome intensities

Color fundamentals

- Color – Perceptual result of light in the visible region of spectrum as incident on the retina
  - 400 nm to 700 nm
  - White light is result of reflected light balanced across all visible wavelengths
- Characterization of light
  - Achromatic (no color) or monochromatic light characterized by intensity
  - Gray level as a scalar measure from black to white
- Chromatic light
  - Spans the electromagnetic spectrum from approximately 400–700nm
  - Light source characterized by three quantities

    Radiance Total amount of energy emitted by light source, measured in watts
      * Physical power of light energy
      * Expressed in a spectral power distribution, often in 31 components, each representing a 10 nm band

    Brightness Achromatic notion of intensity to describe color sensation
      * Attribute of a visual sensation according to which an area appears to emit more or less light

    Luminance Measure of amount of energy as perceived by an observer, measured in lumens or candelas per square meter
      * More tractable version of brightness, defined by CIE
      * Radiant power weighted by a spectral sensitivity function that is characteristic of vision
      * Luminous efficiency peaks at 555nm
      * CIE luminance, denoted by Y, is the integral of spectral power distribution, using spectral sensitivity curve as a weighting function
      * Magnitude of luminance is proportional to physical power, but spectral composition is related to brightness sensitivity of human vision
      * Units of measurement for image processing
        · Normalized to 1 or 100 with respect to a standard white reference
        · $Y = 1$ is the white reference of a studio broadcast monitor whose luminance is 80 cd/m^2
- Lightness
  - Perceptual response to luminance
  - Nonlinear in nature: a source having a luminance only 18% of a reference luminance appears about half as bright
  - Denoted by L^* and defined as a modified cube root of luminance

$$L^* = 116 \left(\frac{Y}{Y_n}\right)^{1/3} - 16 \qquad\qquad 0.008856 < \frac{Y}{Y_n}$$

  - Y_n is the luminance of the white reference
  - L^* has a range of 0 to 100; $\Delta L^* = 1$ gives the threshold of visibility

- Cones in the eye respond to three colors: red, green, blue
  - 6 to 7 million cones in human eye
  - 65% cones respond to red eye
  - 33% cones respond to green light
  - 2% cones respond to blue light, these being most sensitive
  - Red, green, and blue are known as primary colors
    * In 1931, CIE designated specific wavelengths for primary colors
    * Red – 700nm
    * Green – 546.1nm
    * Blue – 435.8nm
    * To generate all colors, we may have to vary the wavelengths of primary colors while mixing colors; so the three primary colors are neither fixed nor standard

- Color characterized by three quantities

  Hue Dominant color as perceived by an observer (red, orange, or yellow)
    - Attribute of visual sensation that makes an area appear similar to one of the perceived primary colors, or a combination of them
    - Depends on the dominant wavelength of an SPD

  Saturation Relative purity of color; pure spectrum colors are fully saturated
    - Colorfulness of an area judged in proportion to its brightness
    - Inversely proportional to the amount of white light added
    - Runs from neutral gray through pastel to saturated colors
    - Depends on theconcentration of SPD at one wavelength
    - Desaturate a color by adding light at all wavelengths

  Brightness Chromatic notion of intensity

- Chromaticity
  - Combination of hue and saturation
  - Allows a color to be expressed as its brightness and chromaticity

- Tristimulus values
  - Three types of cones in the eye require three components for each color, using appropriate spectral weighting functions
    * Based on standard curves/functions defined by CIE – Commission Internationale de L'Éclairage
    * Curves specify the transformation of SPD for each color into three numbers
  - Amount of red, green, and blue to express a color
  - Denoted by X, Y, and Z
  - Color specified by its tristimulus coefficients

$$
\begin{aligned}
x &= \frac{X}{X+Y+Z} \\
y &= \frac{Y}{X+Y+Z} \\
z &= \frac{Z}{X+Y+Z}
\end{aligned}
$$

  - Note that $x + y + z = 1$
  - Chromaticity diagram
    * Figure 6-05
    * Color given as a function of x and y
    * The corresponding value of z is obtained by $1 - (x + y)$
    * Points on the boundary are fully saturated colors
    * Saturation at point of equal energy is 0
    * Mainly useful for color mixing
      · Any straight line joining two points defines all the color variations obtained by combining the two colors additively
      · Extension to three colors by using a triangle to connect three points
      · Supports the assertion that not all colors can be obtained with three single, fixed primaries as some of them are outside the triangle
      · Figure 6-06 – Color gamut

Color models

- Also called color space or color system
- Allow the specification of colors in some standard way
- Specification of a coordinate system and a subspace within that system
- Models oriented towards hardware (rendering and scanning) or software (reasoning and applications)
- RGB color model
  - Figure 6-07
  - Unit cube
    * Colors defined by vectors extending from origin
  - Pixel depth – Number of bits used to represent each pixel in RGB space
  - Depth of 24-bits when each color represented by 8 bits in the triplet to represent pixel
  - Figure 6-08
  - Rendering an image
    * Figure 6-09
    * Fuse the three color components together
  - Acquiring an image
    * Figure 6-09, but in reverse
    * Acquire individual color planes and put them together
  - Converting RGB to luminance
    * Red, green, and blue components are assigned different spectral weights
    * Rec 709 is the standard followed in most contemporary monitors
    * $Y_{709} = 0.2126R + 0.7152G + 0.0722B$
    * Old NTSC system followed a different weight scheme for the same

$$Y_{\text{NTSC}} = 0.299R + 0.587G + 0.114B$$

- HSI color model

- Hue, saturation, intensity
- RGB and CMY models
  * Ideally suited for hardware implementation
  * RGB matches the human eye's perception for primary colors
  * RGB and CMY not suitable for describing colors for human interpretation
  * Dark or light or pastel colors
  * Humans do not think of color images as being composed of three primary images that form a single images
- Human description of images/colors
  * In terms of hue, saturation, and brightness
- HSI model decouples intensity component from the color-carrying components (hue and saturation)
  * Ideal tool for developing image processing algorithms
  * Natural and intuitive to humans
- Intensity
  * Measure over some interval of the electromagnetic spectrum of the flow of power that is radiated from, or incident on, a surface
  * Linear light measure, expressed in units such as watts per square meter
  * Controlled on a CRT monitor by voltages presented, in a nonlinear manner for each color component
  * CRT voltages are not proportional to intensity
  * RGB color images can be viewed as three monochrome intensity images
  * Extracting intensity from RGB images
    · Stand the RGB color cube on the black vertex, with white vertex directly above it (Figure 6.12)
    · Line joining the black and white vertices is now vertical
    · Intensity of any color given by intersection of intensity axis and a plane perpendicular to it and intersecting with the color point in cube
    · Saturation of color increases as a function of distance from intensity axis
    · Saturation of points along intensity axis is zero (all points on intensity axis are gray)
- Hue
  * Consider the plane defined by black, white, and cyan
  * Intensity axis is contained within this plane
  * All points contained in plane segment given by these three points have the same hue – cyan
  * Rotating the plane about the intensity axis gives us different hues
- Above discussion leads us to conclude that we can convert a color from the RGB values to HSI space by working out the geometrical formulas
  * Primary colors are separated by $120°$
  * Secondary colors are $60°$ from the primaries
  * Hue of a point is determined by an angle from a reference point
    · By convention, reference point is taken as angle from red axis
    · Hue increases counterclockwise from red axis
  * Saturation is the length of vector from origin to the point
    · Origin is given by intensity axis
- Figure 6.14 to describe HSI model

• Converting colors from RGB to HSI
  - Consider RGB values normalized to the range $[0, 1]$

- Given an RGB value, H is obtained as follows:

$$H = \begin{cases} \theta & \text{if } B \leq G \\ 360 - \theta & \text{if } B > G \end{cases}$$

  * It should be normalized to the range $[0, 1]$ by dividing the quantity computed above by 360

- θ is given by

$$\theta = \cos^{-1}\left\{\frac{\frac{1}{2}[(R-G)+(R-B)]}{[(R-G)^2+(R-B)(G-B)]^{1/2}}\right\}$$

  * θ is measured with respect to red axis of HSI space

- Saturation is given by

$$S = 1 - \frac{3}{(R+G+B)}[\min(R, G, B)]$$

- Intensity component is given by

$$I = \frac{1}{3}(R+G+B)$$

- Converting colors from HSI to RGB
  - Consider the values of HSI in the interval $[0, 1]$
  - H should be multiplied by 360 (or 2π) to recover the angle; further computation is based on the value of H
  - RG sector – $0° \leq H < 120°$

$$\begin{aligned} B &= I(1-S) \\ R &= I\left[1 + \frac{S\cos H}{\cos(60° - H)}\right] \\ G &= 3I - (R+B) \end{aligned}$$

  - GB sector – $120° \leq H < 240°$

$$\begin{aligned} H' &= H - 120° \\ R &= I(1-S) \\ G &= I\left[1 + \frac{S\cos H'}{\cos(60° - H')}\right] \\ B &= 3I - (R+G) \end{aligned}$$

  - BR sector – $0° \leq H < 360°$

$$\begin{aligned} H' &= H - 240° \\ G &= I(1-S) \\ B &= I\left[1 + \frac{S\cos H'}{\cos(60° - H')}\right] \\ R &= 3I - (G+B) \end{aligned}$$

- Figure 6.15
  - HSI components of RGB cube, plotted separately
  - Discontinuity along the $45°$ line in the hue figure
- Manipulating HSI component images
  - Figure 6.16 – image composed of primary and secondary RGB colors and their HSI equivalents
    * In hue, red region maps to black as its angle is $0°$

  - Individual colors changed by changing the hue image
  - Purity of colors changed by varying the saturation
  - Figure 6.17a – Change red and green pixels in Figure 6.16a to 0 (compare with Figure 6.16b)
  - Figure 6.17b – Change saturation of cyan component in Figure 6.16c to half
  - Figure 6.17c – Reduce the intensity of white region in Figure 6.16d by half
  - Figure 6.17d – Combine the three HSI components back into RGB image

Basics of full-color image processing

- Two major categories of processing
  1. Process each component of image (RGB or HSI) individually and then form a composite processed color image
     - Each component can be processed using gray-scale processing techniques
  2. Work with color pixels directly, treating each pixel as a vector

$$\mathbf{c} = \begin{bmatrix} c_R \\ c_G \\ c_B \end{bmatrix} = \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

     - Since each pixel is a function of coordinates (x, y), we have

$$\mathbf{c}(x, y) = \begin{bmatrix} c_R(x, y) \\ c_G(x, y) \\ c_B(x, y) \end{bmatrix} = \begin{bmatrix} R(x, y) \\ G(x, y) \\ B(x, y) \end{bmatrix}$$

     - Each component of the vector is a *spatial* variable in x and y
- The two methods may or may not produce equivalent results
  - Scalar versus vector operations
  - Neighborhood processing will be an example where we get different results

Color transformations

- Process the components of a color image within the context of a single color model, without converting components to different color space
- Formulation
  - Model color transformations using the expression

$$g(x, y) = T[f(x, y)]$$

    T is the operator over a neighborhood of input image f
  - Each $f(x, y)$ component is a triplet in the chosen color space
  - Figure 6.30 – Various color components of an image
  - Must consider the cost of converting from one color space to another when looking at the operations
  - Modifying intensity of an image in different color spaces, using the transform

$$g(x, y) = kf(x, y)$$

    * In HSI color space, converting a pixel h, s, i to h', s', i'

$$
\begin{aligned}
h' &= h \\
s' &= s \\
i' &= ki
\end{aligned}
$$

    * In RGB color space, converting a pixel r, g, b to r', g', b'

$$
\begin{bmatrix} r' \\ g' \\ b' \end{bmatrix} = k \cdot \begin{bmatrix} r \\ g \\ b \end{bmatrix}
$$

    * In CMY color space

$$
\begin{aligned}
c' &= kc + (1 - k) \\
m' &= km + (1 - k) \\
y' &= ky + (1 - k)
\end{aligned}
$$

  - Simple operation in HSI but cost to convert to HSI may not be justifiable
    * Figure 6.31, using $k = 0.7$

- Color complements
  - Hues directly opposite one another on the color circle
    * Figure 6.32
  - Analogous to gray scale negatives
  - Can be used to enhance details buried in dark regions of an image
  - Figure 6.33
    * May not have the same saturation in negative image in HSI
    * Figure shows saturation component unaltered

- Color slicing
  - Used to highlight a specific range of colors in an image to separate objects from surroundings
  - Display just the colors of interest, or use the regions defined by specified colors for further processing
  - More complex than gray-level slicing, due to multiple dimensions for each pixel
  - Dependent on the color space chosen; I prefer HSI
  - Figure 6.34

Tone and color corrections

- Used for photo enhancement and color reproduction
- Device independent color model from CIE relating the color gamuts
- Use a color profile tomap each device to color model
- CIE L*a*b* system
  - Most common model for color management systems

– Components given by the following equations

$$
\begin{aligned}
L* &= 116 \cdot h\left(\frac{Y}{Y_W}\right) - 16 \\
a* &= 500\left[h\left(\frac{X}{X_W}\right) - h\left(\frac{Y}{Y_W}\right)\right] \\
b* &= 200\left[h\left(\frac{Y}{Y_W}\right) - h\left(\frac{Z}{Z_W}\right)\right]
\end{aligned}
$$

where

$$
h(q) = \begin{cases} q^{\frac{1}{3}} & \text{if } q > 0.008856 \\ 7.787q + \frac{16}{116} & \text{otherwise} \end{cases}
$$

– X_W, Y_W, and Z_W are values for refence white, called D_{65} which is defined by $x = 0.3127$ and $y = 0.3290$ in the CIE chromaticity diagram

– X, Y, Z are computed from rgb values as

$$
\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} 0.412453 & 0.357580 & 0.180423 \\ 0.212671 & 0.715160 & 0.072169 \\ 0.019334 & 0.119193 & 0.950227 \end{bmatrix} \begin{bmatrix} R_{709} \\ G_{709} \\ B_{709} \end{bmatrix}
$$

  ∗ Rec. 709 RGB corresponds to D_{65} white point

– L*a*b* is calorimetric, perceptually uniform, and device independent

– L*a*b* decouples intensity from color

  ∗ a* gives red minus green

  ∗ b* gives green minus blue